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Rice yield potential, gaps and constraints during the past three decades in a climate-changing Northeast China

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ABSTRACT

Northeast China (NEC) is one of the most important rice production areas in China, accounting for approximately 15% of its total national rice production, and is one of the regions most vulnerable to global climate change. Knowing crops' potential yields is crucial to understanding comparisons of different cultivars, crops and environments as well as plausible future increases and limits to crop yields. To mitigate the impacts of climate change and enhance food security, investigating yield potential (YP), attainable yield (YP_A), nitrogen-limited potential yield (YP_N), and actual farmers' yield (Y_a) as well as rice yield gaps and their causes in NEC under the climate change background is necessary. In this study, the ORYZA (v3) crop model was calibrated and validated for rice phenology and yields. The validated model was then used to determine YP, YP_A and YP_N values as well as yield gaps caused by nitrogen management factors (YG_{AN}) and other agronomic and socioeconomic factors (YG_{Na}) for five agroclimatic zones in NEC from 1981 to 2010. The regional area-weighted mean YP levels estimated by the model were 12.9 t ha^{-1} for YP and 11.6 t ha^{-1} for YP_A with decreasing trends and 8.7 t ha^{-1} for YP_N with an increasing tendency. The Y_a was 6.8 t ha^{-1}, with a significant increase of 1.1 t ha^{-1} per decade ($p < 0.01$), and farmers achieved 58.6% of the YP. The YP_A accounted for 80.9–94.8% of the YP in NEC. The regional exploitable yield gap (YG_E) was 4.8 t ha^{-1}. The regional yield gaps were shrinking at 0.47 and 0.88 t ha^{-1} per decade for YG_{AN} and YG_{Na}, respectively. In conclusion, because of the persistently large yield gap between farmers and YP_N, YP_A provides the government and farmers an opportunity to significantly increase rice production by controlling socioeconomic factors and adopting high-yield agronomic management practices based on site-specific conditions, including optimized irrigation and fertilization practices and "super" rice cultivars.

1. Introduction

From 1880 to 2012, the global average temperature has increased by 0.85 °C, and this general warming is especially obvious in the mid- and high-latitude areas of the northern hemisphere (IPCC, 2013). Previous studies have indicated that northeast China (NEC) is one of the areas in China most susceptible to climate change (Yang et al., 2015). The average temperature in NEC increased by 0.38 °C per decade during the past five decades, while the duration of sunshine simultaneously decreased by 42 h per decade (Yang et al., 2015). On the other hand, NEC is an important japonica rice production region, wherein rice production accounts for 53% of the national total japonica rice production (National Bureau of Statistics of China, 2016). The rice planting area accounts for approximately 28% of the total grain crop area in NEC. Hence, NEC plays a vital role in food security in China, and rice yields in NEC have the potential to directly affect Chinese national rice production (Zhang et al., 2014).

Yield potential (YP) is defined as the yield of an adapted crop cultivar when grown in favourable environmental conditions in which water and nutrient supplies are not limited and weeds, pests, diseases and other stresses are effectively controlled (Bhatia et al., 2008; Evans and Fischer, 1999). Hence, the potential yield for a certain cultivar in a

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given location is determined by the characteristics of solar radiation, temperature, soil and plant density (Evans and Fischer, 1999; Grassini et al., 2009; Ittersum and Rabbinge, 1997; Zhao and Yang, 2018). Crops' YPs becomes essential to assessing the comparisons of different cultivars, crops and environments as well as for plausible future increases and limits to crop yields. However, it is difficult for farmers to control non-limiting irrigation and fertilization conditions in the field. Therefore, the concept of attainable yield (YP_A) was proposed and discussed by many scientists (Mueller et al., 2012; Liu et al., 2016; Lv et al., 2015). YP_A is the yield achieved by high-yield practices and serves as the meaningful YP level to estimate the exploitation ceiling by farmers in a region (Balasubramanian and Sombilla, 2000). The nitrogen-limited potential yield (YP_N) is commonly less than the YP_A and obtained under the traditional farmers' nitrogen management programme (Laborte et al., 2012). Actual farmers' yield (Y_a) represents the average farmers' yields in a given target area at a given time and in a given ecosystem. The Y_a in a region is commonly much lower than the YP_A for crops because the latter is simulated under high-yield nitrogen and irrigation management programmes in the absence of pests and diseases (Lobell et al., 2009). The gap between YP_A and Y_a is defined as the exploitable yield gap (YG_E). As illustrated in Fig. 1, the YG_E was divided into two components among three yield levels by different constraints. The first yield gap component is between YP_A and YP_N (YG_{AN}) and is mainly due to differences in nitrogen fertilizer factors as a result of using traditional inputs or practices by farmers (Ahrens et al., 2010; Matson et al., 1998). YG_{AN} can be narrowed by using improved nitrogen fertilization management practices. The second yield gap component is between YP_N and Y_a (YG_{Na}) and is caused by other agronomic and socioeconomic factors. These factors may be some of disease, insect, weed, irrigation management and delayed management practices due to weather or other resource constraints (Laborte et al., 2012; Lobell et al., 2009).

Analysis of YP levels is the basis for interpreting yield gaps and constraints, and many previous researchers have used different methods to estimate potential yields for crops. Considering the limiting factors of climate and soil and many reduced forms, empirical models for example, gradually descending models, agroecological zones (AEZ), and global agroecological zones (GAEZ), have been adopted to analyse crop potential yields in specific environments (Fischer et al., 2002; Jiang et al., 2013). Remote sensing and field experiment methods are also used in potential yield studies (Lobell et al., 2009). Crop growth models have been widely and increasingly used to evaluate crop potential yield (Bouman et al., 2001; Liu et al., 2016; Subash et al., 2012) and can dynamically simulate crop growth, development, and yield under various environmental, cultivar, and agronomy management conditions.

Previous literature has empirically suggested that YP_A accounts for 85% or 70–85% of the YP (Balasubramanian and Sombilla, 2000; van Ittersum et al., 2013; Connor et al., 2011). However, these ratios(YR_{AP}) were not fixed values or ranges among the different crops and regions. To distingiush YR_{AP} in different NEC regions, the ratio of rice YP_A to YP (YR_{AP}) was discussed in this research. To our knowledge, this is the first study to evaluate the rice YR_{AP} in NEC. Also, most yield gap studies use only a single definition of potential yields (Lobell et al., 2009). Few comprehensive studies on rice yield gaps have been conducted in NEC, and moreover, no regional analyses of nitrogen constraints or other agronomic and socioeconomic constraints for rice ecosystems in the context of climate change have been conducted in NEC. For the time being, yield gap constraints limit rice producers from increasing their productivity, and narrowing the yield gap and further increasing rice production are vitally important for ensuring food security in NEC.

The objectives of this study were to (1) evaluate the performance of the ORYZA (v3) crop model (Li et al., 2017) for simulating rice development and yields under potential and nitrogen-limited conditions in NEC; (2) investigate the time-series trends of rice YP, YP_A, YP_N, and Y_a at both the agroclimatic zone (CZ) level and in the NEC region overall; and (3) quantify the YR_{AP} and rice yield gaps caused by nitrogen factors, other agronomic factors and socioeconomic factors in NEC under the background of a changing climate. In this study, the ORYZA(v3) model, which has been proven to be a useful tool to investigate the potential impacts of climate and nitrogen management on rice yield (Espe et al., 2016; Li et al., 2017), was employed to assess the different annual YP levels for rice cultivars widely cropped from 1981 to 2010.

2. Materials and methods

2.1. Study region and agroclimatic zones

The study region comprised three provinces in NEC, Heilongjiang (north), Jilin (centre), and Liaoning (south), which are representative of the japonica rice planting regions in China. We selected the counties that had rice cultivation areas larger than 5000 ha consecutively from 2006 to 2010 as the major rice-growing areas (Fig. 2) (Liu et al., 2016).

The three levels of yield potential, Y_a, and yield gap values were estimated at the county level and then scaled up to CZs based on the climate similarity. The study region was clustered into five CZs (Fig. 2) by a method defined by Licker et al. (2010) using growing degree day (GDD) data, which are vitally important to rice planting in NEC (Han, 1999). The GDD was calculated as described in Ramankutty et al. (2002) as follows:

$$GDD = \sum_{i=a}^{b} \max(0, T - T_{base}) \quad (1)$$

where T is the daily mean temperature (°C), T_{base} is the base temperature for rice, a and b are the beginning and end dates, respectively, of the rice growing season in the study region. The T_{base} value in this study was 10 °C (Han, 1999), and the period with a daily mean temperature consecutively greater than 10 °C was defined as the rice

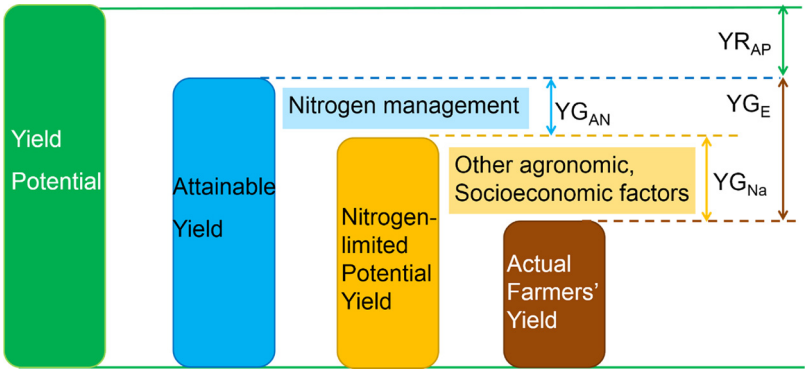

Fig. 1. The concept of yield gaps between potential, attainable, nitrogen-limited, and actual farmers' yields and their main constraints.

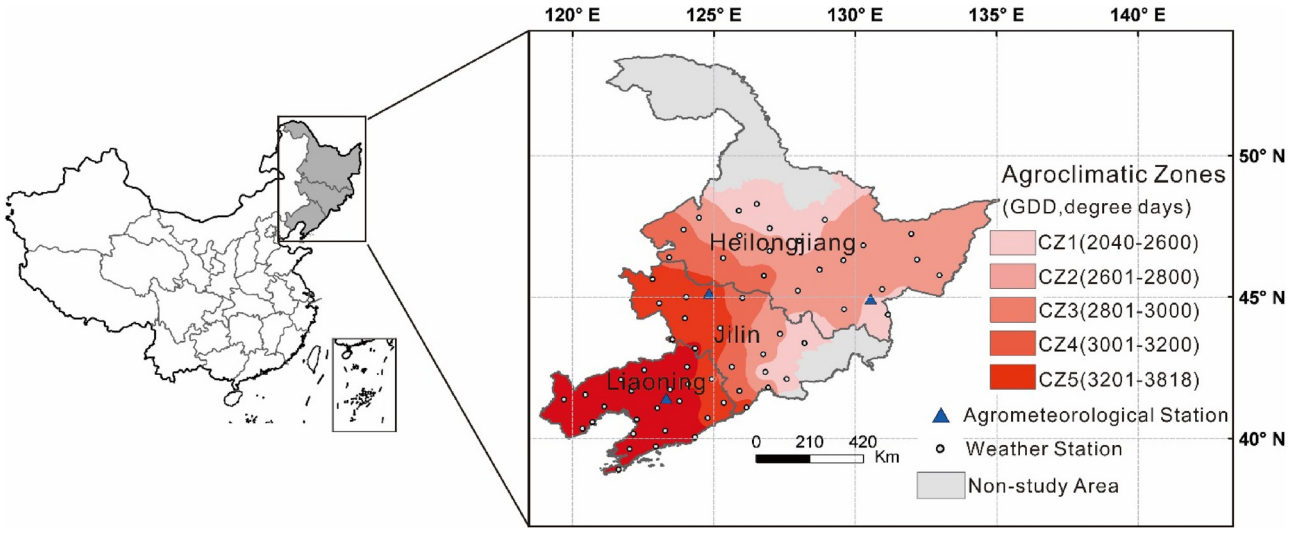

Fig. 2. The locations and agroclimatic zones selected for simulations of potential yield, attainable yield and nitrogen-limited potential yields in NEC. The open circles indicate locations of CMA weather stations. The triangles indicate locations of agrometeorological stations used for model calibration and validation. The colourful shadings indicate the agroclimatic zones in NEC. The grey lines represent the provincial boundaries.

growing season (Han, 1999).

In NEC, the GDD varied from 2040 to 3818 °C days, and the GDD ranges were divided into five groups with equal intervals, defined as the five CZs (Fig. 2).

2.2. Climate, soil, rice phenology and yield data

Historical climate data from 1981 to 2010 were obtained from the climate data-sharing service system (http://data.cma.cn//) of the China Meteorological Administration (CMA). In total, 63 climate stations were utilized, which provided complete records for daily mean temperature, maximum temperature, minimum temperature, sunshine hours, vapour pressure, wind speed and precipitation for the past 30 years (Fig. 2). For simulations of ORYZA (v3) crop model, sunshine hour data were converted to solar radiation using the Ångström formula (Angstrom, 1924; Black et al., 2010).

Soil data, including the bulk density (BD), texture (sand and clay content), pH, and soil organic matter (SOM), in different soil layers were extracted from the soil database of Institute of Soil Science, Chinese Academy of Sciences (ISSCAS).

Rice trial data, including the phenological dates (emergence, transplantation, panicle initiation, flowering and physiological maturity), cultivar type, yield and management practices (planting density, irrigation and fertilizer), were collected from CMA agrometeorological experimental stations. In our study, the most frequently used and regionally representative cultivars at experimental stations were selected and assumed to be province-specific. Rice trial data from Dengta Station of Liaoning Province, Qianguo Station of Jilin Province and Muling Station of Heilongjiang Province, and climate data from the corresponding nearest weather stations were used for the calibration and validation of ORYZA (v3) model. The calibration and validation datasets are presented in Table 1.

The Y_a represented the yield level achieved by farmers in counties. The county yields and planting areas for the period 1981–2010 were obtained from National Bureau of Statistics of China. We selected 63 data pairs which have both types of crop yield and the county meteorological station data. Hence, Y_a was compared with simulated potential yields to quantify rice yield gaps for regional and agroclimatic levels in NEC (Liu et al., 2016).

Table 1
Description of calibration and validation dataset for the ORYZA (v3) crop model from three agrometeorological stations located in three provinces, respectively.

Province	Experimental Station	Cultivar	Calibration Dataset	Validation Dataset
Liaoning	Dengta	LJ294	1998, 2000 ~ 2002	2003 ~ 2005
Jilin	Qianguo	WYD	2000 ~ 2002	2003 ~ 2005
Heilongjiang	Muling	SY397	2000 ~ 2002	2003, 2005 ~ 2007

2.3. The ORYZA (v3) crop model

The ORYZA (v3) crop model was developed to simulate the growth, development, and yield of rice, water and nitrogen balances in rice fields under potential production, and water- and nitrogen-limited situations (Li et al., 2017). For all situations, the crops were presumably well protected against diseases, pests, and weeds. A detailed description of ORYZA model was given by Bouman et al. (2001). The model has been widely used for a range of applications across climate scenarios and regional research (Laborte et al., 2012; Li et al., 2017; Zhang et al., 2014). In this study, we selected a representative cultivar from each province to specify crop coefficients using the model calibration (Table 1), and the specified cultivar coefficients were used in the subsequent modelling analysis.

ORYZA (v3) was parameterized for phenological development following the procedure established by Li et al. (2016) and Yuan et al. (2017) using the DRATES calibration programme and the calibration dataset (Table 1, 4 years at Dengta Station in Liaoning Province, 3 years at Qianguo Station in Jilin Province and 3 years at Muling Station in Heilongjiang Province). The other parameters that linked with biomass productivity and allocation to organs at different stages were calibrated by finding the crop parameters that optimized the model performance with the AutoCalibration program (Li et al., 2016; Yuan et al., 2017). The description and values of the calibrated parameters are presented in Table 2. A validation dataset (Table 1, 3 years at Dengta Station in Liaoning Province, 3 years at Qianguo Station in Jilin Province and 4 years at Muling Station in Heilongjiang Province) was used to validate the prediction capability of model on rice yield.

To evaluate the performance of the ORYZA (v3) crop model, statistical indices of the correlation coefficient (R^2), normalized root mean

Table 2
Description and calibrated values of the selected parameters in the ORYZA (v3) model for this study.

Parameter[a]	Description	Unit	LJ294	WYD	SY397
TBD	Base temperature for development	°C	7	6	6
TBLV	Base temperature for juvenile leaf area growth	°C	8	7	7
TMD	Maximum temperature for development	°C	37	36	36
TOD	Optimum temperature for development	°C	27	26	25
DVRJ	Development rate in juvenile phase	$°Cd^{-1}$	0.0006288	0.0007097	0.0037419
DVRP	Development rate in panicle development phase	$°Cd^{-1}$	0.0009261	0.0012291	0.0008507
DVRR	Development rate in reproductive phase	$°Cd^{-1}$	0.0015349	0.0016087	0.0017789
KDF0.00	Light extinction coefficient of rice canopy at DVS = 0	Unitless	0.45	0.45	0.50
KDF0.65	Light extinction coefficient of rice canopy at DVS = 0.65	Unitless	0.45	0.45	0.50
KDF1.00	Light extinction coefficient of rice canopy at DVS = 1	Unitless	0.60	0.60	0.65
KDF2.50	Light extinction coefficient of rice canopy at DVS = 2.5	Unitless	0.40	0.40	0.70
FSTR	Fraction of carbohydrates allocated to stems that is stored as reserves	Fraction	0.17	0.20	0.115
FLV0.00	Shoot dry matter partitioned to the leaves at DVS = 0	Fraction	0.45	0.60	0.60
FLV0.50	Shoot dry matter partitioned to the leaves at DVS = 0.5	Fraction	0.45	0.60	0.60
FLV0.64	Shoot dry matter partitioned to the leaves at DVS = 0.64	Fraction	0.25	0.60	0.40
FLV0.84	Shoot dry matter partitioned to the leaves at DVS = 0.84	Fraction	0.20	0.00	0.30
FST0.00	Shoot dry matter partitioned to the stems at DVS = 0	Fraction	0.55	0.40	0.40
FST0.50	Shoot dry matter partitioned to the stems at DVS = 0.5	Fraction	0.55	0.40	0.40
FST0.64	Shoot dry matter partitioned to the stems at DVS = 0.64	Fraction	0.75	0.40	0.60
FST0.84	Shoot dry matter partitioned to the stems at DVS = 0.84	Fraction	0.20	0.30	0.55
FST1.00	Shoot dry matter partitioned to the stems at DVS = 1	Fraction	0.10	0.20	0.20
FSO0.84	Shoot dry matter partitioned to the panicles at DVS = 0.84	Fraction	0.60	0.70	0.15
FSO1.00	Shoot dry matter partitioned to the panicles at DVS = 1	Fraction	0.80	0.80	0.70

[a] The first 7 parameters are derived from the field observed data. The other 4 parameter group are directly included in the calibration process.

squared errors (NRMSE), and Willmott's index of agreement (D) between simulated and observed data were calculated. R^2 and D values closer to 1 and lower NRMSE indicate good agreement and low model bias between the observed and simulated variables (Willmott, 1982).

2.4. Potential, attainable and nitrogen-limited potential yields

The ORYZA (v3) model was run to estimate YP, YP_A, YP_N values using the historical climate data (1981–2010) under three potential scenarios as described below:

(i) YP: The ORYZA(v3) model was run in the potential production mode (Bouman et al., 2001). The irrigation and nitrogen fertilization modules were set to "POTENTIAL" in the experiment file to enable the water and nitrogen supplying as the requirement of maximum crop growth. There is no water and nutrient stresses during the rice growing season when simulating YP.

(ii) YP_A: The ORYZA (v3) model was run in the dynamic water and nitrogen balance mode (Bouman et al., 2001). The technology and management consisting of nitrogen, irrigation management, and planting density used in ORYZA (v3) model were the same as rice high-yield research plots in Liaoning, Jilin and Heilongjiang Provinces of NEC (Kong, 2016; Liu et al., 2009; Yan et al., 2017) (Table 3). For nitrogen management, fertilizer rate on the day after the transplant and the days when the developmental stage (DVS) = 0.4, DVS = 0.65 and DVS = 1.2, in the model represented the actual application rates at transplanting, tillering, panicle initiation and end of flowering, respectively.

(iii) YP_N: The ORYZA (v3) model was run in the dynamic water and nitrogen balance mode (Bouman et al., 2001). Under this scenario, the traditional farmers' irrigation and nitrogen managements were used. The nitrogen, irrigation management and sowing density values were averaged from local famers' management programmes in the Liaoning, Jilin and Heilongjiang Provinces (Kong, 2016; Liu et al., 2009; Yan et al., 2017) (Table 3).

Other management coefficients containing emergence dates and seed bed durations were province-specific and set to the average value

Table 3
Model configuration for different management for each cultivar.

Province	Cultivar	Emergence	Seed-bed Duration	Planting Density	Nitrogen Regime ($kg\,ha^{-1}$)		Irrigation Regime
		Julia Day	Days	(Plant m^{-2})	Amount	Ratios TP:TL: PI: EF	
YP							
Liaoning	LJ294	111	32	92	Potential	Potential	Potential
Jilin	WYD	116	29	130	Potential	Potential	Potential
Heilongjiang	SY397	129	25	140	Potential	Potential	Potential
YP_A							
Liaoning	LJ294	111	32	92	225	1:1:1:0	Flooded
Jilin	WYD	116	29	130	154	4:3:2:1	Flooded
Heilongjiang	SY397	129	25	140	150	4:3:1:2	Flooded
YP_N							
Liaoning	LJ294	111	32	69	225	1:1:0:0	Flooded
Jilin	WYD	116	29	78	154	1:1:0:0	Flooded
Heilongjiang	SY397	129	25	84	150	1:1:0:0	Flooded

Note: For the nitrogen fertilizer application schedule, TP, TL, PI and EF indicated the application at transplanting, tillering, panicle initiation and end of flowering, respectively. For the irrigated scheme, "Flooded" indicated that an automatic irrigation system was used to maintain a 10–50 mm water depth. The "potential" implied the supply of nitrogen or water completely matched the requirement of the maximum crop growth under a given climate condition.

Table 4
Long-term average values of the yield levels (YP, YP_A, YP_N, and Y_a), yield gaps (YG_{AN}, YG_{Na}, and YG_E), YP_A to YP ratio (YR_{AP}) and yield gap fractions ($YG_{AN}f$, $YG_{Na}f$, and YG_Ef) in each CZ and NEC.

Region	YP t ha^{-1})	YP_A	YP_N	Y_a	YG_{AN}	YG_{Na}	YG_E	YR_{AP} (%)	$YG_{AN}f$	$YG_{Na}f$	YG_Ef
CZ1	13.2	11.7	8.0	5.8	3.7	2.2	5.9	88.6	31.6	27.5	50.4
CZ2	12.3	11.4	8.3	6.6	3.1	1.7	4.8	92.7	27.2	20.5	42.1
CZ3	12.9	11.1	8.7	6.6	2.4	2.1	4.5	86.0	21.6	24.1	40.5
CZ4	13.6	11.0	9.5	7.9	1.5	1.6	3.1	80.9	13.6	16.8	28.2
CZ5	13.4	12.7	9.1	6.7	3.6	2.4	6.0	94.8	28.3	26.4	47.2
NEC	12.9	11.6	8.7	6.8	2.9	1.9	4.8	89.9	25.0	21.8	41.4

of rice trial data from the agrometeorological experimental stations.

2.5. Data statistical analyses

(i) To quantify the climate change trends during the period from 1981 to 2010, we calculated the mean temperature and solar radiation in the rice growing season for each meteorological station. The crop growing season was determined by the method introduced in Section 2.1.

(ii) To quantify the ratio of YP_A to YP, YR_{AP} was calculated using Eq. (2).

$$YR_{AP} = YP_A/YP \tag{2}$$

(iii) To calculate the yield gaps, data representing the three modelled levels and Y_a were obtained for the 63 stations in the study region based on the definition of yield levels. For each station, the yield gaps were defined as follows:

YG_E is the difference between YP_A and Y_a (Eq. (3)).

$$YG_E = YP_A - Y_a \tag{3}$$

The yield gap caused by nitrogen factors (YG_{AN}) is the difference between YP_A and YP_N (Eq. (4)).

$$YG_{AN} = YP_A - YP_N \tag{4}$$

The yield gap caused by other agronomic and socioeconomic factors (YG_{Na}) is the difference between YP_N and Y_a (Eq. (5)).

$$YG_{Na} = YP_N - Y_a \tag{5}$$

The constraints of nitrogen factors (YG_{AN} faction) was calculated according to Eq. (6).

$$YG_{AN}f = \frac{YP_A - YP_N}{YP_A} \times 100\% \tag{6}$$

The constraints of other agronomic and socioeconomic factors (YG_{Na} faction) was calculated according to Eq. (7).

$$YG_{Na}f = \frac{YP_N - Y_a}{YP_N} \times 100\% \tag{7}$$

(iv) For each station, we used linear regression analysis to detect yield level trends and yield gap levels. The slope of the linear regression line of yield against time was evaluated by Student's t-test confidence intervals of 95% or 99%. Linear regression analysis was also used to detect trends in changes in climatic variables, including the mean daily temperature and solar radiation for the rice growing season (Kruger and Shongwe, 2004). Spatial interpolations for GDD, average temperature and solar radiation were based on the inverse distance weighting (IDW) method in ArcGIS software (ArcGIS Desktop, Redlands, CA, USA).

3. Results

3.1. ORYZA (v3) crop model calibration and evaluation

The performance of the simulated model compared with regional observations is shown in Fig. 3, illustrating that the ORYZA (v3) model confidently estimated the key phenology days and grain yields of the representative cultivars in both the calibration and validation datasets. The correlation (R^2) and D values between the simulated and observed values were close to 1.0 (0.57 to 0.99, 0.84 to 0.99, respectively), while the NRMSE values were less than 8%. These results indicate that the ORYZA (v3) crop model can simulate rice phenology and yield with good accuracy for different cultivars selected from NEC. The ORYZA (v3) crop model reliably simulated different levels of potential yield.

3.2. Potential yield, attainable yield, nitrogen-limited yield, and actual farmers' yield

The mean temperature for the entire rice growing season in NEC ranged from 11.2 °C in the north to 20.6 °C in the south. Solar radiation for the rice growing season ranged from 3066 MJ m^{-2} in the east to 3643 MJ m^{-2} in the west. Moreover, the mean temperature during the rice growing season increased, and the solar radiation decreased in most of the selected locations but not significantly (Fig. 4). Significant and strong temperature warming and radiation decreasing trends for the rice growing season occurred in CZ3 of NEC.

The long-term average YP, YP_A, YP_N, and Y_a values in the five CZs and NEC are presented in Fig. 5 and Table 4. For the entire study region, rice yields of different 30-year area-weighted mean levels during the period from 1981 to 2010 were 12.9 t ha^{-1} for YP, 11.6 t ha^{-1} for YP_A, 8.7 t ha^{-1} for YP_N, and 6.8 t ha^{-1} for Y_a. Among the five CZs, the 30-year area-weighted mean YPs simulated by ORYZA (v3) ranged from 12.3 t ha^{-1} to 13.6 t ha^{-1}, and YP_A values ranged from 11.0 t ha^{-1} to 12.7 t ha^{-1}. However, the YP_N, and Y_a for the area-weighted mean levels were much lower and ranged from 8.0 t ha^{-1} to 9.5 t ha^{-1} and 5.8 t ha^{-1} to 7.9 t ha^{-1}, respectively. YP was mainly determined by total solar radiation and average temperature during the rice growing season. In this study, the highest YP was found mainly in the inland southwest of NEC (CZs 4 and 5, higher than 13.3 t ha^{-1}), where the CZs had better thermal resources. The highest YP_A was located in CZ5 and the highest YP_N and Y_a values were found in CZ4 as a result of the combined effects of better solar radiation, temperature, farmers' agronomic management practices and socioeconomic factors.

Remarkably, the regional means of simulated YP and YP_A values decreased by 0.26 t ha^{-1} and 0.25 t ha^{-1}, respectively, per decade from 1981 to 2010, and the trends were not significant in many CZs (Fig. 6), because of the increasing temperature and decreasing solar radiation (Fig. 4). However, the YP_N and Y_a may be significantly different. The YP_N increased by 0.22 t ha^{-1} per decade because the positive impacts of farmers' nitrogen management had mitigated and offset negative impacts of increasing temperature and decreasing solar radiation on rice yields. The Y_a increased by 1.10 t ha^{-1} per decade ($p < 0.01$) for NEC from 1981 to 2010. Furthermore, Y_a increased significantly for all CZs at average rates of 0.61–1.74 t ha^{-1} per decade (Fig. 6).

3.3. Analysis of the exploitable yield gap

According to the definition of yield potential levels and Fig. 1, the gap between YP and YP_A cannot be narrowed by current technology

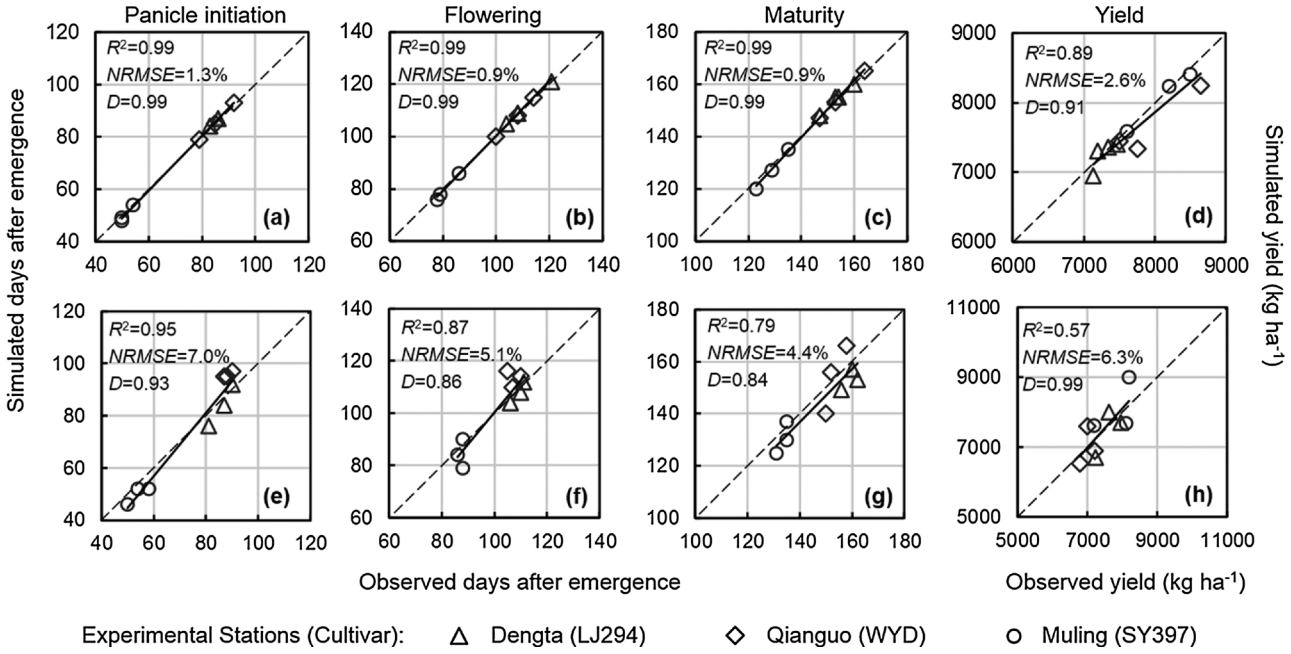

Fig. 3. Comparison of the simulated and observed days after sowing for panicle initiation (a and e), flowering (b and f), physiological maturity (c and g), and grain yield (d and h). The a, b, c, and d show the results using the calibration dataset, and e, f, g, and h show the validation results. The dashed line represents the 1:1 line, and the values of R^2, NRMSE, D are presented in each figure.

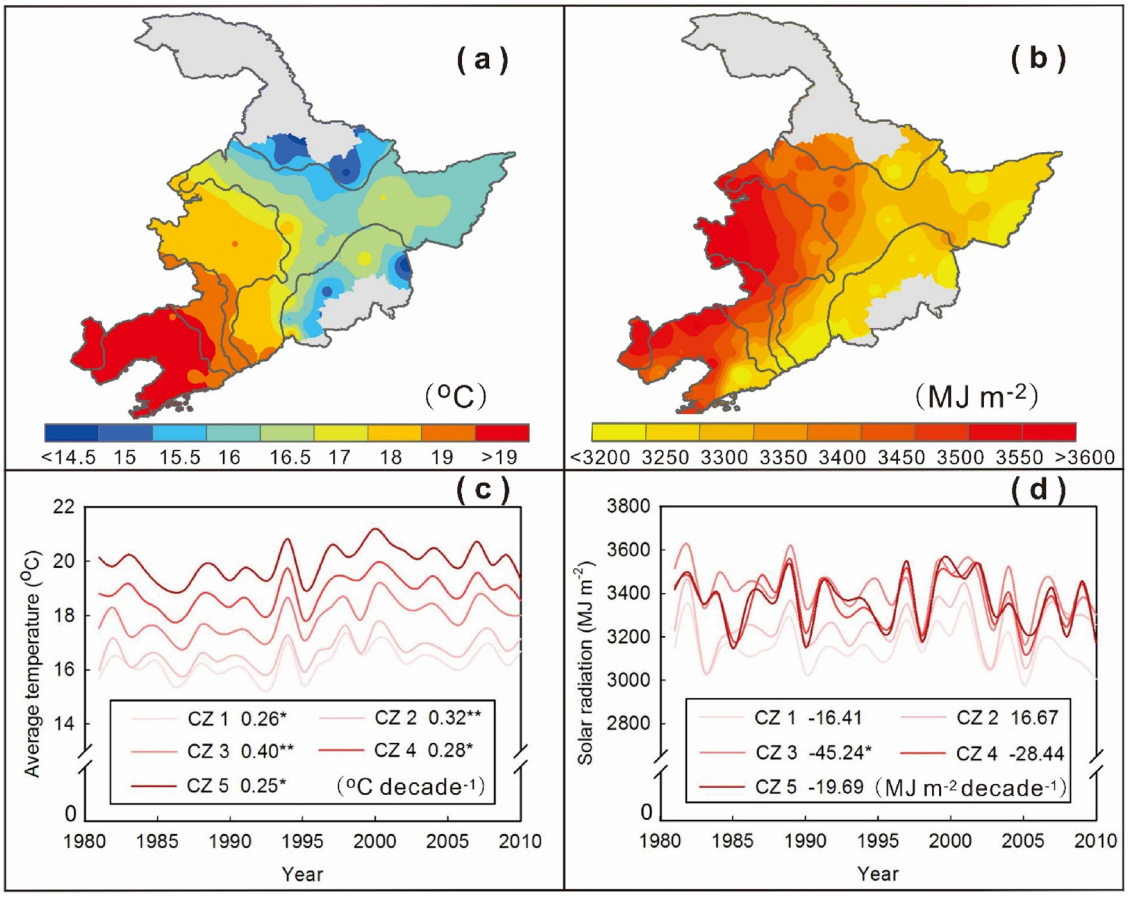

Fig. 4. Spatial distributions of (a) average temperature and (b) solar radiation and time series of (c) average temperature and (d) solar radiation during the rice-growing season from 1981 to 2010 in each agroclimatic zone (CZ). The block charts in the bottom of panel (c) and (d) show the linear trends of temperature (°C decade^{-1}) and solar radiation (MJ m^{-2} decade^{-1}). The grey lines represent the CZ boundaries. * Significant at $p < 0.05$. **Significant at $p < 0.01$.

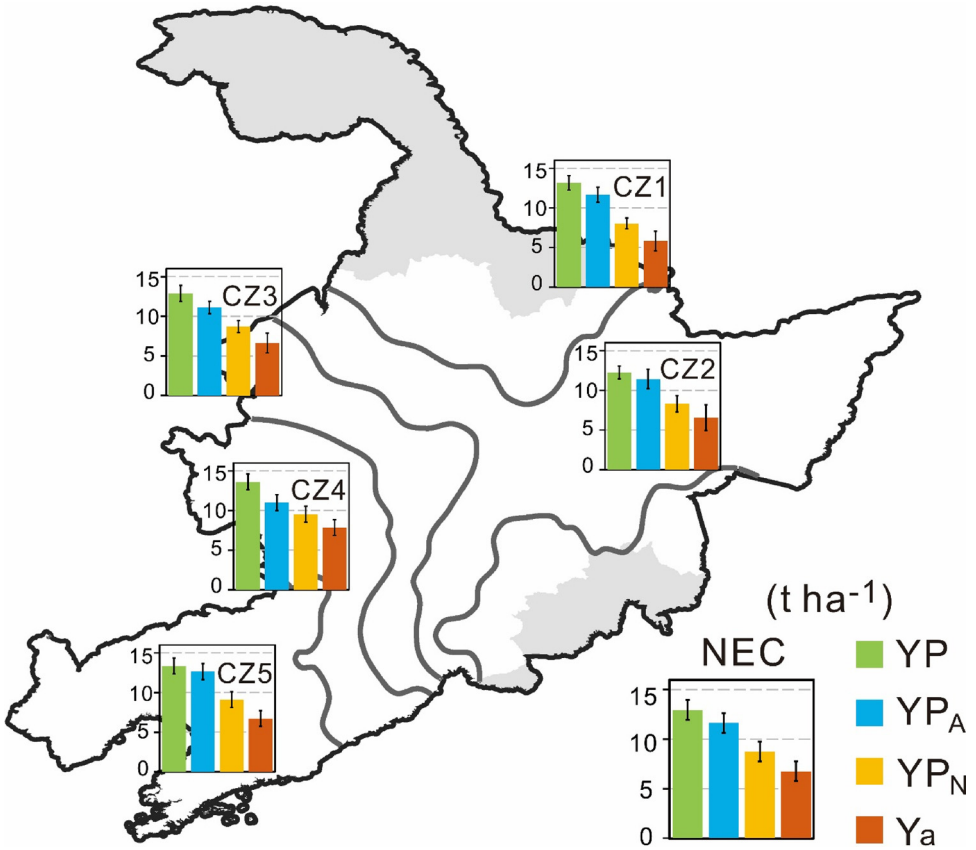

Fig. 5. Potential yield (YP), attainable yield (YP_A), nitrogen-limited potential yield (YP_N), and actual farmers' yield (Y_a) of rice (t ha^{-1}) from 1981 to 2010 in the entire NEC and in agroclimatic zones CZ1 to CZ5. The grey lines represent the CZ boundaries.

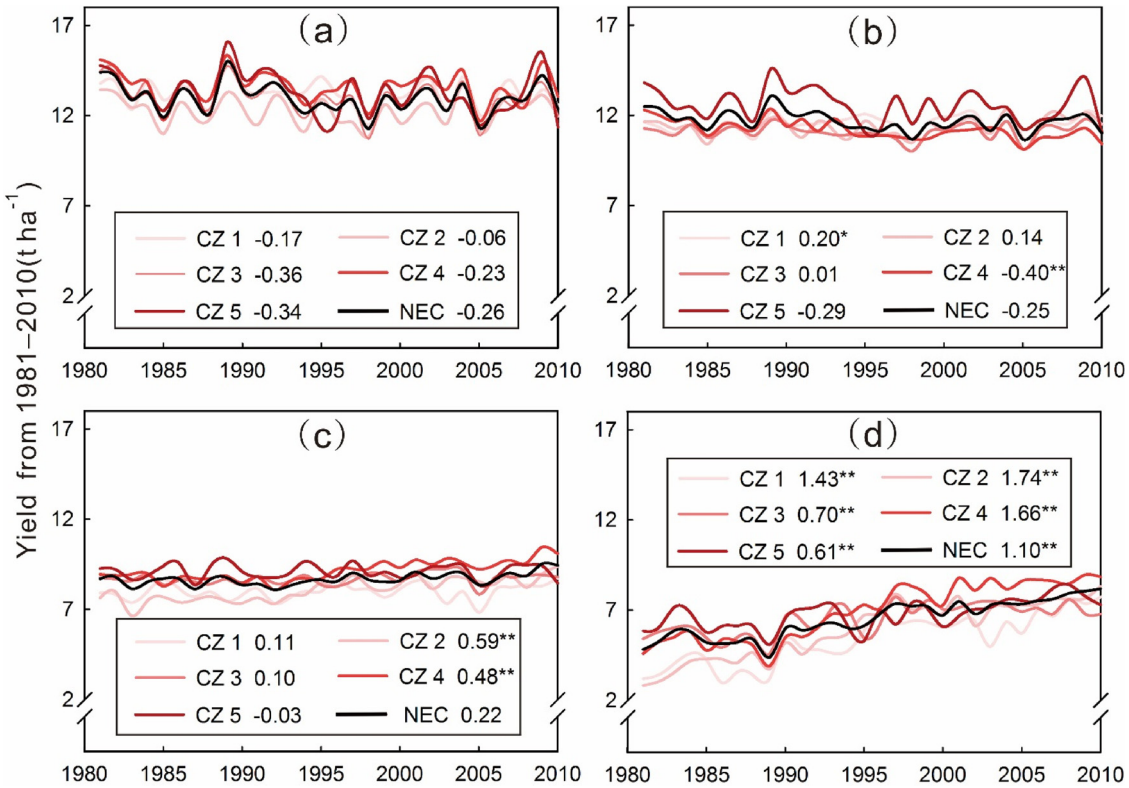

Fig. 6. Time series of rice (a) YP, (b) YP_A, (c) YP_N, and (d) Y_a (t ha^{-1}) in each CZ and NEC from 1981 to 2010. The tables in the subfigures show the linear trends of YP, YP_A, YP_N, and Y_a (t ha^{-1} $decade^{-1}$) in each CZ and NEC. ** and * indicate significance at $p < 0.01$ and $p < 0.05$, respectively.

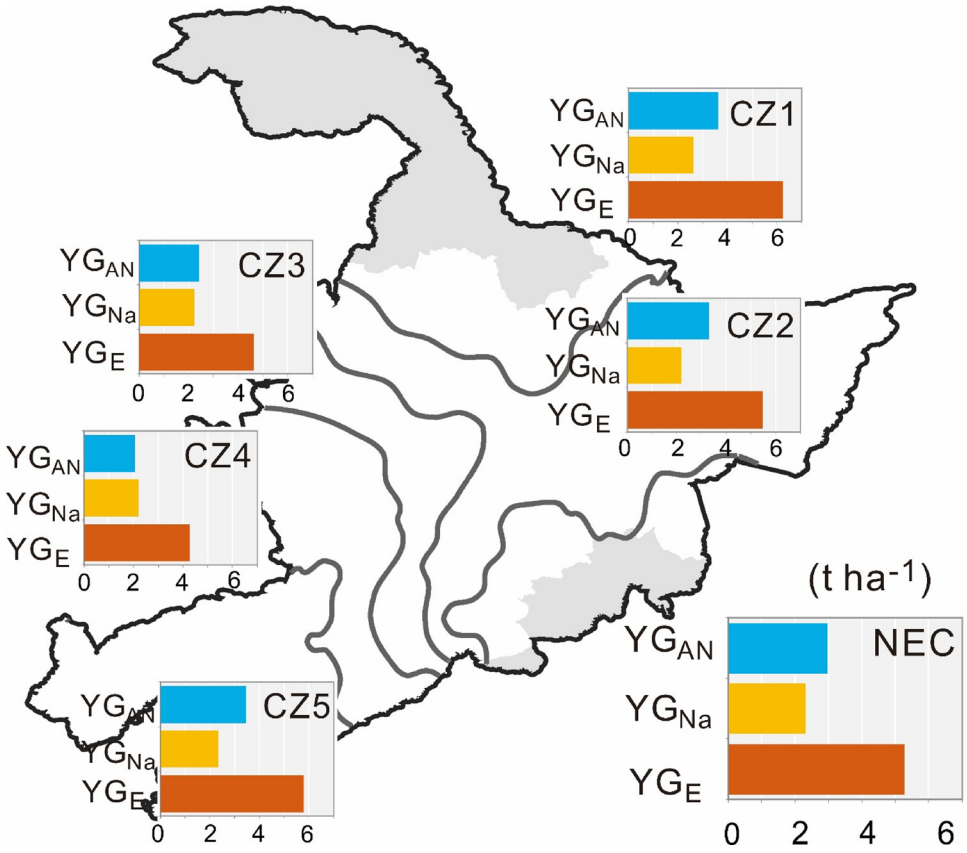

Fig. 7. Area-weighted mean yield gaps (t ha^{-1}) of rice in CZs and NEC from 1981 to 2010. The blue, orange and brown columns indicate YG_{AN}, YG_{Na} and YG_E, respectively. The grey lines represent the CZ boundaries (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

and management. The 30-year mean YP_A estimated by the ORYZA (v3) model with high-yield management practices approached 80.9%–94.8% of the YP in five CZs of NEC. In this study, we regarded the YP_A as the yield potential that farmers could exploit under high-yield conditions.

The area-weighted mean of YG_E from 1981 to 2010 was 4.8 t ha^{-1} for rice throughout all of NEC, which indicates that rice yields achieved by farmers in NEC reached only 41.4% of the YP_A during the study period (Table 4). Spatial and temporal variabilities of rice YG_E were observed in NEC (Figs. 7 and 8). The 30-year mean YG_E varied from 3.1 to 6.0 t ha^{-1} among CZs. The YG_E of CZs 1, 2 and 5 were higher than the regional average, which suggested that Y_a in these areas (for example, northwest of Heilongjiang Province and Jilin Province and south of Liaoning Province) could be increased more by applying improved agronomic practices. The YG_E of rice located in CZ4 was lowest, where the Y_a reached 58.1% of the YP_A. Given the decreases in YP_A and increases in Y_a, YG_E decreased during the past three decades with rates varying from 0.7 to 2.1 t ha^{-1} per decade ($p < 0.01$) among the five CZs. For all of NEC, the YG_E showed a significant decreasing trend of 1.3 t ha^{-1} per decade from 1981 to 2010.

3.4. Yield gaps caused by nitrogen and other agronomic and socioeconomic factors

In Fig. 1, the exploitable yield gap (YG_E) was divided into two components among three yield levels by different constraints. The two yield gap components in different climate zones and NEC were determined and the temporal trends of yield gaps were assessed.

For the entire study region, rice yield gaps from 1981 to 2010 were 2.9 t ha^{-1} for YG_{AN} and 1.9 t ha^{-1} for YG_{Na} (Table 4). The area-weighted mean YG_{AN} of NEC accounted for 25.0% of the YP_A because of the farmers' fertilizer management factors. Notably, the YG_{AN} over the period 1981 to 2010 varied among CZs. The greatest YG_{AN} (3.7 t ha^{-1}) was located in CZ1 (blue shadings in Fig. 7). A noticeably low yield gap of only 1.5 t ha^{-1} was found for CZ4. During the past three decades, the regional YG_{AN} mean was estimated to decrease by 0.47 t ha^{-1} per decade from 1981 to 2010. Among the five CZs, YG_{AN} in CZ1 presented a slight increasing trend (0.09 t ha^{-1} per decade), while the other CZs decreased at rates of 0.09–0.88 t ha^{-1} per decade (Fig. 8).

The YG_{Na} was 1.9 t ha^{-1} for NEC (21.8% of YP_N, limited by local agronomic and socioeconomic factors), indicating that farmers can potentially reap 78.2% of the YP_N. The area-weighted mean YG_{Na} varied from 1.6 to 2.4 t ha^{-1} among the five CZs (orange shading in Fig. 7). Greater values (27.5% of YP_N) were located in CZ1, especially north of Heilongjiang Province and east of Jilin Province. The YG_{Na} time trend was significant among the five CZs, decreasing from 0.6 to 1.3 t ha^{-1}per decade from 1981 to 2010 (Fig. 8).

4. Discussion

In this study, we integrated to examined the spatial and temporal trend patterns of rice potential and actual yields at regional levels. The yield potentials, attainable yields, nitrogen-limited potential yields, and actual farmers' yields within agroclimatic zones in Northeast China were determined. The quantitative ratio of YP_A to YP and yield gaps, were calculated for rice in our research region.

The ORYZA (v3) crop model has a reliable capability to simulate rice growth, development and yield in non-stressed, water-stressed and nitrogen-stressed environments. It can accurately determine rice yield potential levels under various scenarios (Laborte et al., 2012; Li et al., 2017; Zhang et al., 2014). The ORYZA model has been evaluated to simulate rice yields under changing climatic and environmental conditions in rice-growing regions of China (Yuan et al., 2017; Zhang et al., 2014). In this research, with the observed phenologies and yields of widely planted hybrids, the well-calibrated and validated ORYZA (v3) model was applied to estimate three levels of rice yield potentials at weather stations across NEC from 1981 to 2010.

YP is defined as the yield of an adapted crop cultivar when grown in

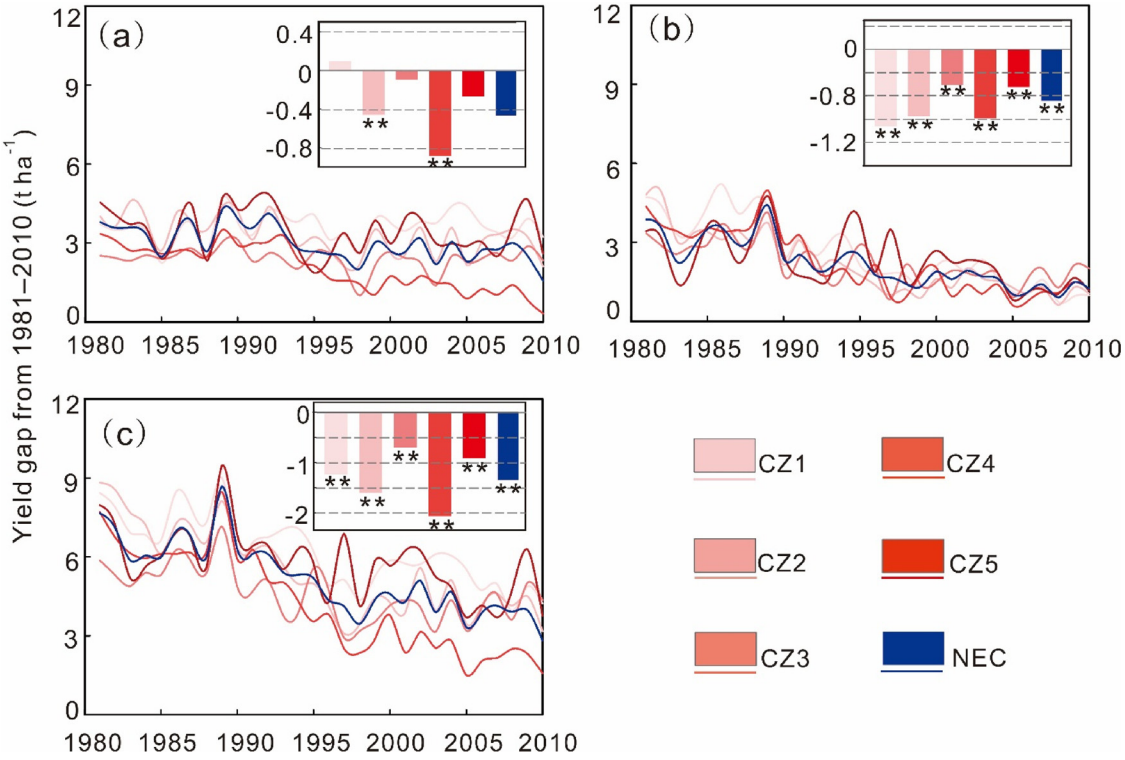

Fig. 8. Yield gaps (t ha^{-1}) of rice for each CZ and NEC from 1981 to 2010. Panels a, b and c indicate the temporal change trends (t ha^{-1} $decade^{-1}$) of YG_{AN}, YG_{Na} and YG_E, respectively. ** and * indicate statistical significance at $p < 0.01$ and $p < 0.05$, respectively.

a favourable environment (Bhatia et al., 2008; Evans and Fischer, 1999) and is mainly determined by solar radiation and temperature. During the period from 1981 to 2010, the area-weighted mean YP was 12.9 t ha^{-1} in NEC and decreased from west to east, with the same spatial distributions of temperature and solar radiation. Although the values in our study were reasonably more or less than those from previous studies (Jiang et al., 2013; Zhang et al., 2014), the spatial patterns were almost the same. The CZs with better temperature and radiation resources, e.g., CZ4 and CZ5, obtained higher YPs (more than 13 t ha^{-1}). Accordingly, the rice YP of CZ2, wherein the temperature and solar radiation were lower, was lowest (12.3 t ha^{-1}) among the five CZs. During the past three decades, omitting the effects of carbon dioxide (CO_2) concentration by using average value of last three decades (360 ppm) in simulation, the decreasing YPs with fixed cultivars indicated the negative impacts of climate change including climate warming and solar radiation decrease on yields and the shrinking improvement space for furthering YPs. The trend was also consistent with research on other crops that climate warming will shorten their growing seasons and possibly reduce yields (Liu et al., 2016). However, the atmospheric concentration of CO_2 has approximately increased from 340 ppm to 390 ppm over the period 1981 to 2010 (IPCC, 2013), and the fertilizer effects of rising CO_2 concentration should not be ignored. The yield loss may be partially compensated by the CO_2 fertilization effects if the increasing CO_2 concentration were considered (Xiong et al., 2012; Xu et al., 2018). Furthermore, the rice Y_a in NEC significantly increased from 1981 to 2010 (Fig. 6), which was largely attributed to improved rice varieties and fertilizer management (Xu et al., 2016; Zhang et al., 2016). As previous studies have illustrated, varieties renewal and management improvement contributed 34% and 16% to rice Y_a increase, respectively for NEC (Zhang et al., 2016).

The YP was mainly determined by solar radiation and temperature, and under this YP-simulated environment, fertilizer and water were applied to rice upon lacing throughout the entire growing cycle (Bhatia et al., 2008; Evans and Fischer, 1999; Liu et al., 2016). However, actual fertilizer and irrigation management practices cannot adhere to this perfect situation. Therefore, YP_A, which can be achieved by farmers with high-yield management practices under field conditions, has been discussed in recent manuscripts (Balasubramanian and Sombilla, 2000; van Ittersum et al., 2013; Connor et al., 2011). Previous studies have suggested that the YP_A values were 85% or 70–85% of the YPs (Balasubramanian and Sombilla, 2000; van Ittersum et al., 2013; Connor et al., 2011). However, these ratios were not fixed for different crops in different areas. Therefore, identifying the YR_{AP} in different regions of NEC is necessary. In our study, the YP_A with the best management was 80.9–94.8% of the YP among the five CZs for NEC. The higher values may have been due to the highly intensified irrigation system and high-yield management practices.

Furthermore, gaps between YP_A and Y_a were discussed to interpret the yield that can be exploited by improving farmers' field technology and positive socioeconomic drivers. According to our estimated results, the 30-year mean YG_E for NEC was 4.8 t ha^{-1}, indicating that farmers achieved only 58.6% of the YP_A. Our results were reasonably higher than those of Lobell et al. (2009) for China because of the inter-regional differences. Decreases in the YG_E were attributed to substantial increases in farmers' yields and stagnation in the potential yields with no adaptation management practice (Zhang et al., 2014). Moreover, based on the definitions of yield levels shown in Fig. 1, "nitrogen management" and "other agronomic and socioeconomic factors" accounted for the differences between YP_A and YP_N, between YP_N and Y_a, respectively. Also, YG_E directly associated with the impacts of nitrogen management, other agronomic factors (field weed and irrigation management, novel agricultural practices, etc.) and socioeconomic factors. The YG_E, YG_{AN}, and YG_{Na} decreased significantly at rates of 0.5 ~ 1.4 t ha^{-1} per decade in NEC from 1981 to 2010. Although yield gaps had a decreasing trend, the NEC yield gaps remained large because farmers achieved only 49.6% to 71.8% of the YP_A. Among five CZs in NEC, YG_{AN} and YG_{Na} of CZ1 and CZ5 were the highest. In these two CZs, farmers can largely narrow YG_{AN} by deploying more effect to improve nitrogen management strategies, and narrow YG_{Na} by improving other agronomic (field weed and irrigation management, novel agricultural

practices, etc.) and positive socioeconomic factors. These facts have implications for producers and researchers to pay attention to improve yield by mitigating the impact of the rice yield constraints. As previous studies have illustrated, average grain yields would increase by approximately 7–12% using the improved fertilizer practice (Sui et al., 2013; Xu et al., 2016), and "super" hybrid rice could increase rice yields by 8–15% (Peng et al., 2009); Furthermore, integrated management practices, including nutrient, water, and other agronomic options, accounted for much of the yield gains, which could increase by 30% compared to those currently being achieved by farmers' practices (Qin et al., 2013). These facts have implications for producers and researchers to pay attention to improve yield by mitigating the impact of the rice yield constraints.

Overall, based on the ORYZA (v3) model, we identified different levels of potential yield and yield gaps in spatial and temporal distribution trends for rice in five CZs and NEC from 1981 to 2010, aiming to provide a scientific basis for optimized field management practices and rice production improvements. Based on the results, rice producers and decision-makers can understand the impacts of yield constraints for developing rice planting strategies and local policies by mitigating the limiting factors (Liu et al., 2016; Espe et al., 2016). However, this research had some limitations. Briefly, consistent rice cultivars and constant CO_2 concentration were used for each station when YPs were simulated during the research period to eliminate the effects of them in this study. However, the positive contributions of cultivar improvement and increased CO_2 concentration to the yields of many crops have been shown in previous studies (Challinor et al., 2016; Long et al., 2006; Lv et al., 2015; Peng et al., 2009; Tao et al., 2013). Also, neither potassium (K) and phosphorous (P) fertility nor weed and pest management were not analysed because ORYZA (v3) model does not have the capability to address these factors (Bouman et al., 2001). The constraints limiting crop yield gaps (nitrogen factors, other agronomic factors and socioeconomic factors) were clarified, but the specific contributions of management practices and new rice cultivars to decreasing trend of yield gaps were not decoded in this study. Finally, this study did not consider the influence of water-saving irrigation techniques, such as alternate wetting and drying (Devkota et al.,2015; Peng et al.,2009), which should also be an important aspect to study in the future with ground and surface water salinization (Licker et al., 2010; Tilman, 1999). In the future, the contributions of CO_2 concentration, new higher-yielding rice cultivars and more detailed management practices to yield potential and yield gaps should be studied. Therefore, better-integrated rice management practices can be established at each station to help policy makers and farmers narrow the yield gap and serve as a scientific basis for researchers.

5. Conclusions

To identify rice yield gaps caused by nitrogen factors, other agronomic factors and socioeconomic factors, we used the ORYZA (v3) model to investigate potential rice yields at 63 climate stations in NEC on the climate change background from 1981 to 2010. The results suggest that the estimated regional means of rice YP, YP_A and YP_N were 12.9 t ha^{-1}, 11.6 t ha^{-1} and 8.7 t ha^{-1}, respectively, while the Y_a was only 6.8 t ha^{-1}. At the same time, due to the negative effects of increasing temperatures and decreasing solar radiation, the mean simulated YP and YP_A decreased by 0.26 and 0.25 t ha^{-1}, respectively, per decade. In contrast, YP_N and Y_a were increased by 0.22 and 1.10 t ha^{-1} per decade ($p < 0.01$), respectively. The YP_A and Y_a implied that the regional area-weighted mean YG_E was 4.8 t ha^{-1}, 41.4% of the YP_A. Analysis of yield-constraining factors showed that the limits of rice yield induced by nitrogen factors as well as by other agronomic and socioeconomic factors were 25.0 and 21.8%, respectively. The large gaps between simulated YP_A and Y_a indicate the existence of an opportunity to significantly increase rice productivity in the NEC region. The YG_E was found to have significantly decreased by 1.3 t ha^{-1} per decade, which revealed that the shrinking yield gap was largely contributed to increasing farmers' yields.

The constraints of nitrogen factors were much higher than those of other agronomic and socioeconomic factors. During the past three decades, YG_{AN} constrained by nitrogen management factors decreased slightly. Therefore, in the coming decade, advisors and farmers should focus on reducing this yield gap by improving nitrogen fertilizer practices, e.g., optimizing the amount of nitrogen input and fertilizer time during the rice growing period.

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